

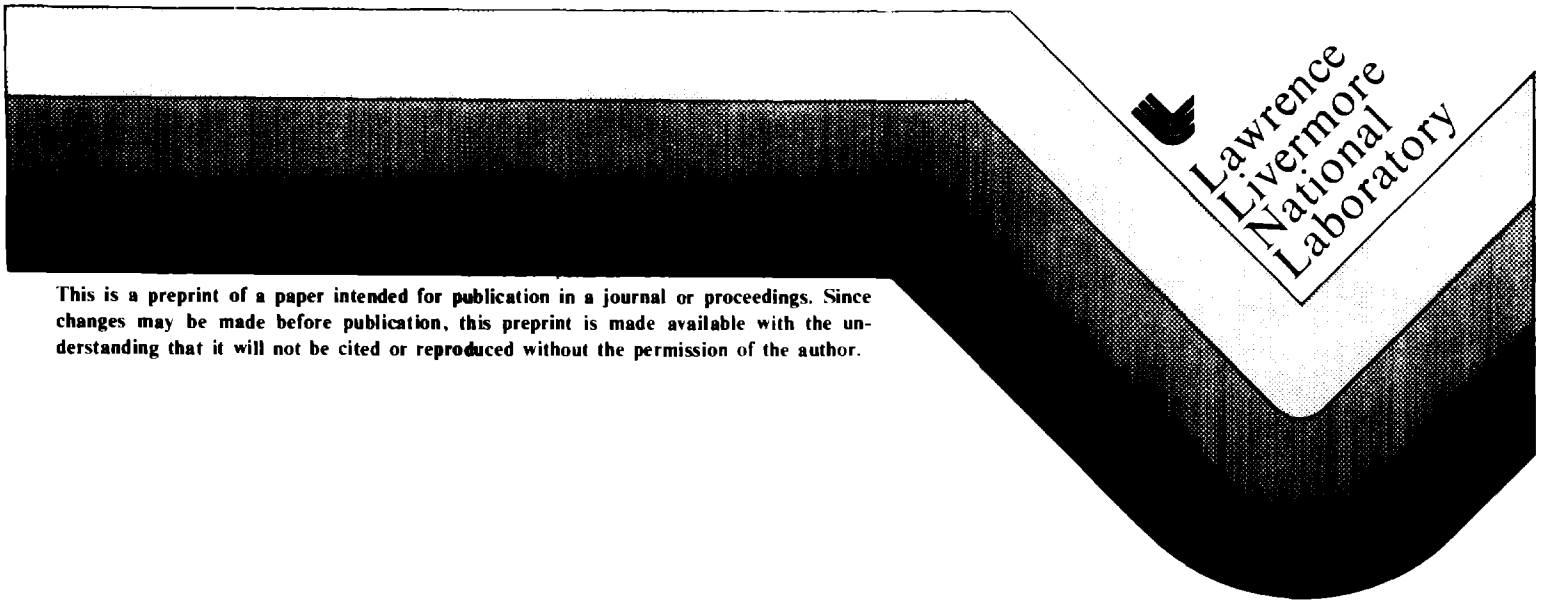
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SPHERICAL TUNGSTEN POWDER

W. H. Gourdin  
S. L. Weinland

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# DYNAMIC COMPACTION OF A MONOSIZED SPHERICAL TUNGSTEN POWDER

W. H. Gourdin and S. L. Weinland  
University of California  
Lawrence Livermore National Laboratory  
Livermore, CA

## ABSTRACT

We present a limited number of measurements of the Hugoniot of a 45-74- $\mu\text{m}$  spherical tungsten powder in the stress range 0 to 7 GPa. From these data we infer that compaction to the solid density occurs at about 4 GPa. Examination of recovered specimens shows that interparticle bonding does not occur at stresses as high as 6.2 GPa. This is consistent with calculations based on the energy flux at powder particle surfaces during compaction, which suggest that interparticle melting will not occur at stresses less than about 9.0 GPa.

## INTRODUCTION

Dynamic compaction has received much attention in recent years as a possible means of densifying rapidly solidified powders without substantially altering their initial microstructures.<sup>1-5</sup> The method is also of potential interest in the processing of refractory metal powders, however, because their high melting points make conventional processing difficult and expensive. Boade<sup>6</sup> studied the dynamic response of a sintered porous tungsten with a density of  $12.64 \times 10^3 \text{ kg/m}^3$  over a stress range of 1.2 GPa to over 100 GPa. Emphasis was placed on the wave propagation and equation-of-state aspects of the compaction process, which were analogous to those observed in sintered copper specimens.<sup>7,8</sup> Similarly, early Russian work<sup>9</sup> focused on equation-of-state studies at high stresses ( $>10 \text{ GPa}$ ) and low initial densities ( $<50\%$  of solid). Later studies extended this work<sup>10</sup> but also explored some aspects of plastic flow, densification, and energy deposition at lower stress levels.<sup>11</sup>

In this paper we report the results of a limited number of Hugoniot experiments on unsintered, carefully sized spherical tungsten powder. Our objectives were to define the dynamic densification behavior as a function of stress and to seek evidence for interparticle melting or other local thermal modification of the microstructure in the final compact, predicted to be a maximum for a spherical powder at a given initial density and final stress.<sup>1,2</sup> We first present a description of the experiments and starting materials. We then present our Hugoniot data along with observations of recovered specimens. We conclude with a brief discussion of the results.

## EXPERIMENTAL PROCEDURE

All of the experiments in this study were performed on a 6.35-cm-diam smooth-bore helium-driven gun.<sup>1,3</sup> The specimen assembly, shown in Fig. 1, is the same as that described by Gourdin and Weinland.<sup>1,3</sup> Piezoresistive carbon film sensors<sup>1,4</sup> were affixed to the centers of a 0.3-cm-thick cover plate and a 1.27-cm-thick back plate, both of 6061-T6 aluminum, with a thin ( $<0.0013$  cm) layer of epoxy. Leads from the sensors were brought out the rear of the assembly to bridge circuits used to measure the change in resistance of the sensing element during powder consolidation. Although these sensors are designed to give a direct reading of the stress from the induced change in resistance, the calibration is somewhat uncertain.<sup>1,3</sup> Hence the primary data of this study were derived from impedance matching relative to the aluminum 6061-T6 cover and back plates. The constancy of wave speeds in porous tungsten and copper,<sup>6-8</sup> the apparent steadiness of wave profiles in copper,<sup>8</sup> as well as the success of the approach in describing a variety of metal powders<sup>1,3</sup> indicate that application of the Hugoniot relationships to porous materials is justified. In the configuration used here a shock is produced in the cover plate by a projectile impact, which then releases into the powder along the isentrope rather than the Hugoniot. At the low stresses of concern here, however, the two are very close and the use of the Hugoniot to describe the release path is an excellent approximation. The Hugoniot of aluminum 6061-T6 is complicated by the presence of the Hugoniot elastic limit at about 0.41 GPa (4.1 kbar) that produces an elastic precursor in the cover plate of this amplitude.<sup>1,5,16</sup> This

precursor impinges on the powder specimen about 80 to 90 ns sooner than the slower plastic wave at the lowest projectile speeds we used. Thus the initial loading of the powder specimen is accomplished through a complex series of interactions between reflected and transmitted waves. In practical terms, however, the stress wave introduced into the porous specimen by the precursor in the cover is of small amplitude (0.1-0.2 GPa) and has a correspondingly small propagation speed. In contrast to Boade's observations,<sup>6</sup> we find no evidence for precursor propagation in the powder, and so conclude that this initial wave will be overtaken by the main compaction wave. Although it is very difficult to estimate the wave speed of such a small amplitude wave in the porous specimen, we conservatively estimate it to be about 0.33 km/s, half of the wave speed we observed at the lowest stress, 0.65 km/s. The distance two waves travel in the powder before the compaction wave overtakes the initial wave is given by

$$d = \Delta t / (1/v_1 - 1/v_2) \quad , \quad (1)$$

where  $\Delta t$  is the difference in arrival times at the cover-powder interface, and  $v_1$  and  $v_2$  are the wave speeds of the initial and compaction wave in the powder, respectively. Taking  $\Delta t = 90$  ns,  $v_1 = 0.33$  km/s, and  $v_2 = 0.65$  km/s, we find that  $d$  is approximately  $6 \times 10^{-5}$  m (60  $\mu$ m). This is of the same order as the powder particle size, which defines the minimum width of the compaction shock in the powder.<sup>1,2,7</sup> Hence we conclude that the details of the initial loading of the powder produced by the aluminum cover plate are lost in the slow rise time of the compaction shock and are therefore not important for our experiments. We note also that  $d$  is significantly less than the thickness of the carbon sensors ( $1.27 \times 10^{-4}$  m), a principal source of systematic error.

The impedance matching technique requires that the Hugoniot of the cover and projectile be known. The Hugoniot we have used for aluminum 6061-T6 is described by the shock speed - material speed relationship

$$v_{A1} = 5.35 + 1.34U_p \quad (\text{km/s}) \quad . \quad (2)$$

This was derived from data obtained at stresses in excess of 7.0 GPa,<sup>18</sup> and when extrapolated to low stresses does not describe the details of the elastic response. However, Wallace<sup>15</sup> has noted that a relationship similar to Eq. (2) provides an adequate description of the plastic wave

speeds at low stresses as well. A comparison of the proper aluminum Hugoniot with that given by Eq. (2) shows that for the ranges of stress and particle speed of interest here, the two are barely distinguished. In practical terms, then, we feel (2) is adequate for our experiments.

The dominant source of systematic error is the relatively large thickness of the carbon sensors and the long rise times associated with them (100-200  $\mu$ s in most experiments). Both the transit time and the powder thickness used in calculating the shock speed are significantly affected by this error. We chose the powder thickness to be the distance between the midpoints of the sensors and the transit time to be that between the trigger points. While this approach is somewhat arbitrary, it has nevertheless been successfully applied to more ductile metals that compact to near-solid density.<sup>13</sup> Comparisons of our data with that of Boade<sup>6</sup> and the approach of our data to the proper curve in the limit of complete densification indicate that the systematic errors introduced are not large.

Random errors were calculated in the usual manner,<sup>19</sup> and are shown as error bars in Fig. 3.

The material used in these experiments is a commercially available plasma sprayed powder.<sup>20</sup> Coarse sizing was accomplished by sieving the powder, and final sizing and elimination of irregular particles was carried out on a vibrating "riffler" table. The characteristics of the resulting 45-74- $\mu$ m powder are summarized in Table 1 and Fig. 2. The measured solid density is 2% less than the nominal density of  $19.3 \times 10^3$  kg/m<sup>3</sup>. We attribute this to a small amount of included porosity, and we refer our results to the measured value.

## RESULTS

The Hugoniot data are given in Table 2 and Fig. 3. The Hugoniot derived under the assumption of complete compaction is also shown in Fig. 3 and it is apparent from this, as well as the specific volume data in Table 2, that the powder reaches the solid density for compaction stresses in excess of about 4.0 GPa, in agreement with the observations of Boade.<sup>6</sup> Reshock data for several experiments were obtained directly from the back plate sensor readings, and are shown in Fig. 3. Because of

the high stresses produced upon reshock, however, these readings cannot reliably be corrected for errors in the sensor calibration,<sup>1,3</sup> and are therefore not expected to be accurate. As a result, they are not included in Table 2. Nevertheless, these data clearly demonstrate that the reshock Hugoniot becomes increasingly steep as the compact density behind the primary shock increases.

The cross section of a recovered specimen compacted at approximately 6.2 GPa (projectile speed 0.856 km/s) is shown in Fig. 4. Although badly fractured, it is apparent that the powder was compacted to solid density. The specimen had virtually no cohesive strength, however, and only the small amount shown cohered well enough to survive handling. We found no evidence for any thermal modification of the microstructure as a result of dynamic consolidation.

## DISCUSSION

The microstructure of the recovered specimen (Fig. 4) is characteristic of dynamically compacted spherical powders of ductile metals.<sup>2,1</sup> There is little mechanical interlocking in such compacts, so the lack of substantial compact strength indicates the absence of the interparticle bonding found in dynamically formed specimens of less refractory materials.<sup>1-3,12</sup> From the data in Table 2, we calculate that the energy deposited behind the primary compaction wave in the compact of Fig. 4 is approximately  $1.06 \times 10^5$  J/kg. With the assumption that all of this energy appears at powder particle interfaces, we estimate the maximum surface temperature to be 2150°C,<sup>12</sup> well below the melting point of 3410°C and consistent with the observed lack of specimen cohesion. Extrapolating the Hugoniot in Fig. 3, we find that surface melting is not expected until the stress exceeds about 9.0 GPa. This corresponds to a projectile speed of over 1.1 km/s, beyond the capabilities of our apparatus.

## SUMMARY AND CONCLUSION

We have reported a limited number of Hugoniot measurements for a carefully sized, 45-74- $\mu$ m spherical tungsten powder in the stress range

0 to 7 GPa. From this work we conclude the following:

- (1) Tungsten behaves as a ductile metal and is compacted to the solid density for compaction stresses in excess of about 4.0 GPa.
- (2) Local thermal modification and interparticle bonding (melting) do not occur within the stress range required for complete densification.
- (3) Calculations indicate that melting at particle interfaces will not occur for stresses less than about 9.0 GPa.

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#### REFERENCES

1. W. H. Gourdin and J.E. Smugeresky, Microstructural modification of aluminum-silicon alloy powders during dynamic consolidation, in "Proceedings of the Third Conference on Rapid Solidification Processing: Principles and Technologies," R. Mehrabian, ed., National Bureau of Standards (1983), pp. 565-571.
2. W.H. Gourdin, Local microstructural modification in dynamically consolidated metal powders, Metall. Trans. A, 15A: 1653-1664 (1984).
3. P. Kasiraj, T. Vreeland, Jr., R.B. Schwarz, and T.J. Ahrens, Shock consolidation of a rapidly solidified steel powder, Acta Metall. 32: 1235-1241 (1984).
4. D.G. Morris, The properties of dynamically compacted Metglas 2826, J. Mater. Sci. 17: 1789-1794 (1982).
5. D.G. Morris, Compaction and mechanical properties of metallic glass, Metal Science 14: 215-220 (1980).
6. R.R. Boade, Dynamic compression of porous tungsten, J. Appl. Phys. 40: 3781-3785 (1969).

7. R.R. Boade, Compression of porous copper by shock waves, Ibid. 39: 5693-5702 (1968).
8. R.R. Boade, Principal Hugoniot, second-shock Hugoniot and release behavior of pressed copper powder, Ibid. 41: 4542-4551 (1970).
9. K.K. Krupnikov, M.I. Brazhnik, and V.P. Krupnikova, Shock compression of porous tungsten, Soviet Phys. JETP 15: 470-476 (1962).
10. A.A. Bakanova, I.P. Dudoladov, and Y.N. Sutulov, Shock compressibility of porous tungsten, molybdenum, copper, and aluminum in the low pressure domain, Zhurnal Prikladnoi Mek. i Tek. Fiz. 2: 117-122 (1974).
11. O.V. Roman, V.F. Nesterenko, and I.M. Pikus, Influence of the powder particle size on the explosive pressing process, Fizika Goreniya i Vzryva 15: 102-107 (1979).
12. W.H. Gourdin, Energy deposition and microstructural modification in dynamically consolidated metal powders, J. Appl. Phys. 55: 172-181 (1984).
13. W.H. Gourdin and S.L. Weinland, Hugoniot measurements on unsintered metal powders, in "Shock Waves in Condensed Matter - 1983," J. R. Asay, G. K. Straub, and R. A. Graham, eds., North Holland, New York (1984), pp. 99-102.
14. Dynasen, Inc., Goleta, CA.
15. D.G. Wallace, Flow process of weak shocks in solids, Phys. Rev. B 22: 1487-1494 (1980).
16. J.N. Johnson and L.M. Barker, Dislocation dynamics and steady plastic wave profiles in 6061-T6 aluminum, J. Appl. Phys. 40: 4321-4334 (1969).
17. L. Davison, Shock-wave structure in porous solids, Ibid. 42: 5503-5512 (1971).
18. S.P. Marsh, ed., "LASL Shock Hugoniot Data," University of California Press, Berkeley (1980).
19. W.H. Gourdin and S.L. Weinland, Dynamic compaction of aluminum nitride powder: Hugoniot measurement and comparison with static behavior, submitted to J. Am. Ceram. Soc.; also University of California, Lawrence Livermore National Laboratory, report UCRL-91836 Rev 1 (1985).

20. Sylvania Chemical/Metals, GTE Products Corporation, Hawes Street, Towanda, PA 18848, type SD-351.
21. W.H. Gourdin, Microstructure and deformation in a dynamically compacted copper powder, Materials Science and Engineering 67: 179-184 (1984).

Table 1. Tungsten Powder Characteristics

Characteristic	Value
Nominal composition	99.5 wt% W, 0.15 wt% O
Solid density <sup>a</sup>	$18.93 \times 10^3 \text{ kg/m}^3$
Solid specific volume	$5.2826 \times 10^{-5} \text{ m}^3/\text{kg}$
Packing density	$11.45 \times 10^3 \text{ kg/m}^3$
Relative density	60%
Particle size range	45-74 $\mu\text{m}$
Specific surface <sup>b</sup>	$13.8 \text{ m}^2/\text{kg}$
Area equivalent diameter	23 $\mu\text{m}$

<sup>a</sup> Air comparison pycnometer.

<sup>b</sup> BET method.

Table 2. Hugoniot Data, Tungsten Powder  $11.45 \times 10^3 \text{ kg/m}^3$ 

Expt.	Projectile speed (km/s)	Shock speed (km/s)	Stress (GPa)	Material speed (km/s)	V ( $10^3 \text{ m}^3/\text{kg}$ )
160	0.166	0.65	0.82	0.11	0.07258
159	0.424	0.76	2.33	0.27	0.05605
158	0.657	0.98	4.26	0.38	0.05321
157	0.789	1.11	5.55	0.44	0.05299
156	0.821	1.15	5.90	0.45	0.05332
161	0.854	1.20	6.24	0.46	0.05329

## FIGURES:

Fig. 1. Schematic of the experimental assembly.

Fig. 2. Scanning electron micrograph of the tungsten powder.

Fig. 3. Hugoniot data for unsintered tungsten powder,  $11.45 \times 10^3 \text{ kg/m}^3$  (circles). Error bars refer to the random errors of measurement. Dotted lines connect the primary shock data to the reshock states (diamonds) that lie on the Hugoniot of 6061-T6. The porous Hugoniot derived under the assumption of complete densification is shown. The Hugoniot of solid tungsten and the data of Boade<sup>6</sup> for sintered porous tungsten,  $12.65 \times 10^3 \text{ kg/m}^3$  (shown approximately by the lighter dashed line), are given for reference.

Fig. 4. Cross section of a recovered specimen compacted at a projectile speed of approximately 0.856 km/s. The arrow indicates the propagation direction of the primary compaction wave.

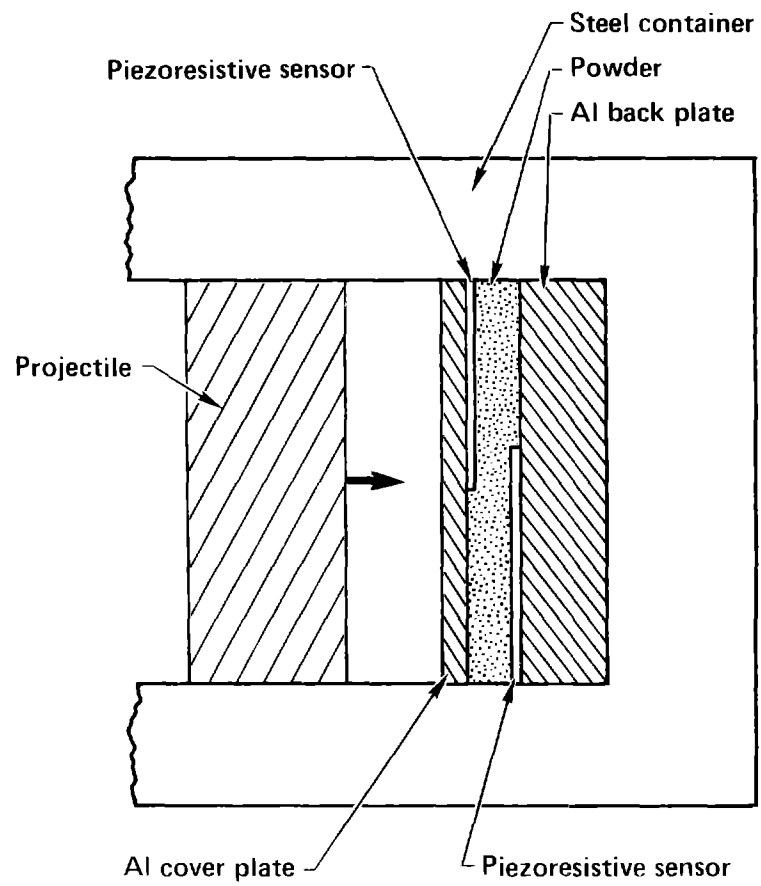


Figure 1

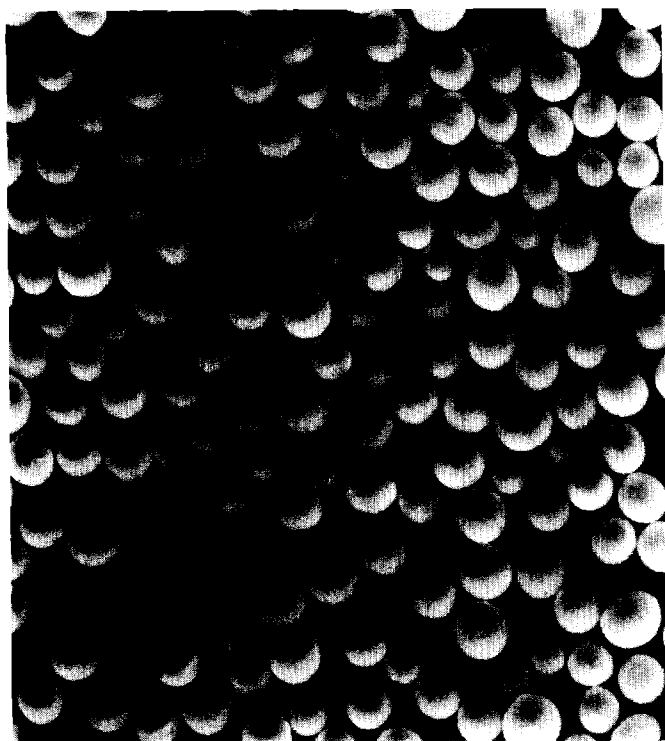


Figure 2

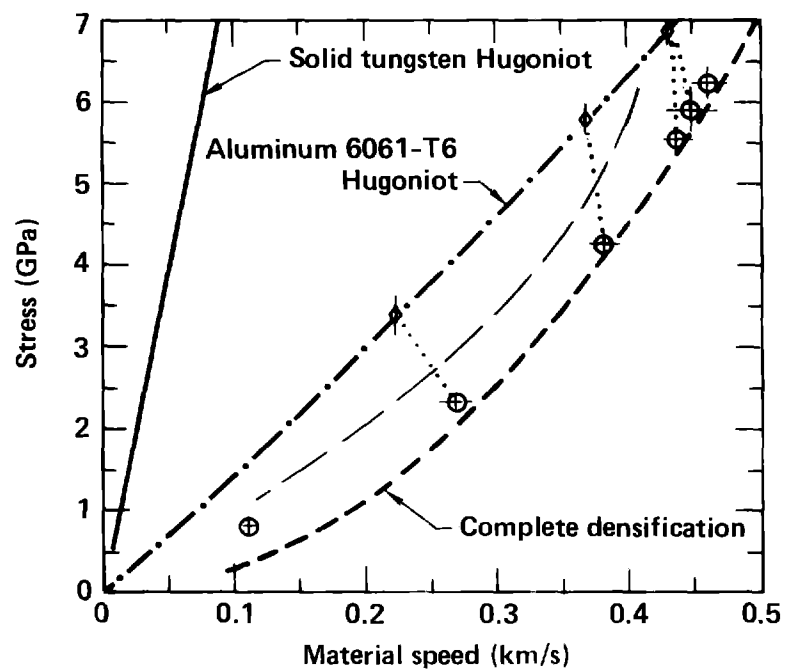


Figure 3



Figure 4